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Lifetime of Ring Current Particles Due to Coulomb Collisions in the Plasmasphere

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Ring current ions and electrons in the trapped belt are scattered and slowed down due to Coulomb interactions with the thermal plasma in the plasmasphere and are eventually removed from trapped orbits. An expression for bounce-averaged Coulomb lifetimes is derived using methods developed by Wentworth et al. (1959) but with the improvements of considering a more realistic representation of the thermal plasma distribution, as a Maxwellian rather than a delta function, and considering heavy ions in the ring current and thermal plasmas. Bounce-averaged Coulomb lifetimes for the major ring current ions are presented and are compared to Coulomb lifetimes in the literature. Coulomb lifetimes for ring current ions with energies less than ~ 10 keV are longer than those predicted using previously derived expressions; however, they are comparable to, or shorter than, charge exchange lifetimes at these energies. For realistic thermal plasma densities in the outer plasmasphere, Coulomb lifetimes for ring current heavy ions can be comparable to charge exchange lifetimes at energies near the peak of the ring current differential number density. These results suggest that Coulomb decay is an important ring current loss process for tens of keV ions and might explain the discrepancy noted by Kistler et al. (1989) between modeled ring current distributions and the ring current fluxes measured by AMPTE/CCE during magnetically active conditions.

1. Introduction

Energetic particles trapped by the geomagnetic field undergo gradient-curvature drifts. This motion of the charged particles plus a magnetization current due to the gyration of these ions generates the ring current around the Earth. The major species which make up the ring current plasma are electrons, protons, helium and oxygen ions. The ring current particles will be lost if they charge exchange with the neutral hydrogen geocorona or are removed by total energy loss and/or pitch angle scattering due to Coulomb collisions with the low-energy thermal charged particles in the plasmasphere. Other possible loss processes, such as moderate pitch angle diffusion, which is the result of interactions with ion cyclotron waves, have also been suggested.

Both the Coulomb collision and the charge exchange loss mechanisms have been widely studied in the past, and charge exchange is considered to be the dominant loss process [e.g., *Kistler et al.* 1989; *Hamilton et al.*, 1988]. In this paper the decay of the ring current caused by Coulomb collisions is investigated further. The Fokker-Planck equation is used to calculate the Coulomb lifetimes of different ring current species. In the calculation the velocity distributions of the plasmaspheric particles are assumed to be Maxwellians. This is an improvement to the calculations of *Wentworth et al.* [1959]. The relative importance of the various ring current loss mechanisms is reexamined in light of these new calculations.

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2. Coulomb Collision Between the Ring Current and the Plasmasphere

Coulomb collisions are a basic interaction between charged particles. When a fast charged particle travels through a plasma, it will be Coulomb scattered by other charged particles and experience energy loss. If the particle is heavier than an electron, energy is transferred to the plasma (mainly to the electrons), without significant angular deflection [*Jackson*, 1962]. An incident electron will be scattered and slowed down by the background electrons [*Jackson*, 1962; *Spitzer*, 1962]. The interaction of the fast-moving charged particle with the background plasma is not binary in nature; the motion of the moving particle is affected by the field of many background plasma particles simultaneously.

In the terrestrial magnetosphere the ring current particles interact with the thermal plasma in the plasmasphere. Ring current particles transfer energy to the plasma in the plasmasphere (dynamical friction), and some are also scattered (diffusion) into the loss cone. Both of these processes cause the loss of ring current particles from their trapped orbits. The rate at which ring current particles are lost due to Coulomb interactions depends on the initial kinetic energy of the particle and on the density n of the plasmasphere population that it encounters. If the pitch angle of a ring current particle is small, it penetrates to low altitudes, where it encounters high background plasma densities, whereas for large pitch angles, the particle remains close to the equator, where the plasma densities are significantly lower. In other words, the plasma density encountered by a ring current particle is a function of its pitch angle at the equator.

3. PREVIOUS WORK

In the process of calculating the lifetime of ring current particles we need to evaluate the effect of the simultaneous Coulomb interaction of a charged particle with all other charged particles in a Debye sphere. In the standard treatment of this problem it is assumed that the interaction can be considered to be a series of weak binary collisions. This approach leads to the Fokker-Planck equation, which is derived from the Boltzmann collision term, and is

$$\left(\frac{\partial f}{\partial t}\right)_{coll} = -\frac{\partial}{\partial v_i}(f < \Delta v_i >) + \frac{1}{2}\frac{\partial^2}{\partial v_i \partial v_j}(f < \Delta v_i \Delta v_j >) \quad (1)$$

where $f = f(t, \vec{r}, \vec{v})$ is the single particle distribution function, normalized as $\int d^3 v f = n(\vec{r})$

$\left(\frac{\partial f}{\partial t}\right)_{coll}$ is the rate of change of f due to collision;

$< \Delta v_i >$ is the coefficient of dynamical friction;

$< \Delta v_i \Delta v_j >$ is the coefficient of diffusion.

and the conventional subscript notation is used. The two coefficients represent the mean rate of change of Δv_i and $\Delta v_i \Delta v_j$, respectively, due to many consecutive weak collisions. Since the interactions take place between particles within a small region in space, we need only consider the velocity dependence of the distribution function.

Rosenbluth et al. [1957] used the Fokker-Planck equation to investigate the distribution functions in a plasma, where the fundamental two-body force obeys an inverse square law. Equation (1) then became

$$\frac{1}{\Gamma_a}\left(\frac{\partial f_a}{\partial t}\right)_{coll} = -\frac{\partial}{\partial v_i}\left(f_a \frac{\partial h_a}{\partial v_i}\right) + \frac{1}{2}\frac{\partial^2}{\partial v_i \partial v_j}\left(f_a \frac{\partial^2 g}{\partial v_i \partial v_j}\right) \quad (2)$$

where

$$\Gamma_a = \frac{Z_a{}^2 e^4 \ln \Lambda}{4\pi\varepsilon_o{}^2 m_a{}^2} \;{}^*$$

$$\Lambda = \frac{\lambda_D}{b_0} \qquad \lambda_D = \text{Debye length}$$

$$b_o = \frac{1}{2}\frac{Z_a Z_b e^2}{4\pi\varepsilon_o m_{ab}}\frac{1}{|\vec{v}_a - \vec{v}_b|^2}$$

$$m_{ab} = \frac{m_a m_b}{m_a + m_b} = \text{reduced mass}$$

the subscript a refers to the scattered species, the subscript b refers to the scattering or field particle in the plasmasphere,

$$h_a(\vec{v}) = \sum_b \frac{m_a + m_b}{m_b}\int d^3 v_1 \frac{f_b(\vec{v}_1)}{|\vec{v} - \vec{v}_1|} \quad (3)$$

$$g(\vec{v}) = \sum_b d^3 v_1 f_b(\vec{v}_1) |\vec{v} - \vec{v}_1| \quad (4)$$

$g(\vec{v})$ and $h(\vec{v})$ are called the Rosenbluth potentials.

Rosenbluth et al. [1957] also adopted gyrotropic distributions and transformed (2) into spherical coordinates in velocity space:

$$f_a = f_a(v, \mu, t)$$

where

$$\mu = \cos\alpha$$

In considering the Coulomb interaction of trapped radiation belt particles with the thermal plasma particles in the plasmasphere, we have a natural axis of symmetry, that is, the direction of the magnetic field. The coefficient α is the pitch angle of the test (a) particles.

Wentworth et al. [1959] used the results of *Rosenbluth et al.* [1957] to derive the Coulomb decay lifetime of trapped particles with a further assumption that

$$\frac{\partial h_a}{\partial \mu} = \frac{\partial g}{\partial \mu} = 0 \quad (5)$$

With (5) the rate of change of the distribution function f_a becomes

$$\frac{1}{\Gamma_a}\left(\frac{\partial f_a}{\partial t}\right)_{coll} = -\frac{1}{v^2}\frac{\partial}{\partial v}\left(f_a v^2 \frac{\partial h_a}{\partial v}\right) + \frac{1}{2v^2}\frac{\partial^2}{\partial v^2}\left(f_a v^2 \frac{\partial^2 g}{\partial v^2}\right) + \frac{1}{2v^2}\frac{\partial^2}{\partial \mu^2}\left(f_a \frac{1-\mu^2}{v}\frac{\partial g}{\partial v}\right) + \frac{1}{2v^2}\frac{\partial}{\partial v}\left(-2 f_a \frac{\partial g}{\partial v}\right) + \frac{1}{2v^2}\frac{\partial}{\partial \mu}\left(f_a \frac{2\mu}{v}\frac{\partial g}{\partial v}\right) \quad (6)$$

Wentworth et al. [1959] made a further simplification, namely, that f_b, the distribution function of the plasmaspheric scattering particles, is a delta function of v_1,

$$f_b(v_1, \mu) = n_b(\mu_e)\,\delta(v_1)$$

where μ_e is the pitch angle at the equator and n_b is the average plasmaspheric density that the ring current particles encounter. The coefficient n_b is a function of the pitch angle of the ring current particle at the equator. Thus μ_e can be used to identify a ring current particle. This approach is valid if the particle makes many traversals before it is appreciably scattered. At the time of the *Wentworth* [1959] article, it was assumed that both the plasmasphere and the radiation belt were composed of protons and electrons. Moreover, $n_b(\mu_e)$ could be approximated by the density at equator, n_e, since they only considered trapped particles with large pitch angles. With all these assumptions and approximations, the bounce-averaged Coulomb decay lifetime of the trapped particles was derived and is given by

*All quantities in the references are in Gaussian units, while S.I. units are used in this paper.

$$\tau_{90\%} = \tau_a \left[1-10^{-3m_a/2m_e k'}\right] \tag{7}$$

where $\tau_{90\%}$ = time for 90% of the particles with mean velocity v_{ao} to be lost,

$$\tau_a = \frac{2\, v_{ao}{}^3 m_e}{3\Gamma_a n_e m_a} \tag{8}$$

m_e is the mass of electron. The k' as a function of the L shell parameter were given by *Wentworth et al.* [1959] and are reproduced in Table 1.

TABLE 1. The Constant k' as a Function of L

	Value					
L	1.1	1.2	1.5	2.0	5.0	10.0
k'	6.0	3.0	1.5	0.98	0.65	0.62

4. COULOMB DECAY OF RING CURRENT IN A MAXWELLIAN PLASMASPHERE

The assumption that the velocity distribution of the plasmasphere is a delta function of $v_l=0$ is valid only when the energy of the ring current particles is much greater than that of the background field particles. In this work we improve on the calculation of *Wentworth et al.* [1959] by assuming that the velocity distribution function of the plasmaspheric plasma population is Maxwellian. We have

$$f_b(\vec{v}_1) = n_b\left(\frac{m_b}{2\pi kT}\right)^{3/2} \exp\left(-\frac{m_b v_1{}^2}{2kT}\right) \tag{9}$$

Given that f_b is a Maxwellian, $h_a(v)$ and $g(v)$, the so-called Rosenbluth potentials, can be expressed as [*Schamel et al.*, 1988] :

$$h_a(v) = \sum_b \frac{m_a+m_b}{m_b}\frac{n_b}{v_b}\frac{\Phi(Y_b)}{Y_b} \tag{10}$$

$$g(v) = \sum_b n_b v_b\left[\left(\frac{1}{2}+Y_b{}^2\right)\frac{\Phi(Y_b)}{Y_b} + \frac{\exp(-Y_b{}^2)}{\sqrt{\pi}}\right] \tag{11}$$

where

$$v_b = \left(\frac{2kT}{m_b}\right)^{1/2}$$

the thermal velocity of species b,

$$Y_b = \frac{v}{v_b} \quad \text{and}$$

$$\Phi(Y_b) = \frac{2}{\sqrt{\pi}}\int_0^{Y_b} e^{-x^2}\,dx$$

the error function.

Before we substitute $h_a(v)$ and $g(v)$ into (6) to solve for f_a we multiply (6) by v^2 and then integrate from $v=0$ to $v=\infty$. The result is

$$\begin{aligned}\frac{1}{\Gamma_a}\frac{\partial N_a}{\partial t} &= \left|-f_a v^2\frac{\partial h_a}{\partial v}\right|_0^\infty \\ &+\frac{1}{2}\left|f_a v^2\frac{d^3 g}{dv^3}+\frac{d^2 g}{dv^2}\left(v^2\frac{\partial f_a}{\partial v}+2vf_a\right)\right|_0^\infty \\ &+\frac{1}{2}\frac{\partial^2}{\partial\mu^2}\left[(1-\mu^2)\int_0^\infty \frac{f_a}{v}\left(\frac{dg}{dv}\right)dv\right] \\ &-\left|f_a\frac{dg}{dv}\right|_0^\infty+\frac{\partial}{\partial\mu}\left[\mu\int_0^\infty\frac{f_a}{v}\left(\frac{dg}{dv}\right)dv\right]\end{aligned} \tag{12}$$

where $N_a = \int_0^\infty v^2 f_a\, dv$ is the particle density per solid angle in velocity space.

Since the total number of particles is finite, $f_a(v=\infty)=0$. By substituting (10) and (11) into (12) we have

$$\begin{aligned}\frac{1}{\Gamma_a}\frac{\partial N_a}{\partial t} &= \frac{1}{2}\frac{\partial}{\partial\mu}\left\{(1-\mu^2)\frac{\partial}{\partial\mu}\left[\int_0^\infty\frac{f_a}{v}\left(\frac{dg}{dv}\right)dv\right]\right\} \\ &-\sum_b\frac{n_b v_b}{\sqrt{\pi}}\left|\frac{\partial f_a}{\partial v}\right|_{v=0}\end{aligned} \tag{13}$$

The second term is set to be zero. This is a valid assumption for most distributions, e.g., Gaussian and delta functions. The integral in the first term can be evaluated if we assign some specific forms to f_a. It was found that the value of this integral is not sensitive to what f_a actually is, so we choose a simple case in the following calculations. We assume that the velocity part of f_a is maximum at $v=v_{ao}$. Therefore we have

$$\int_0^\infty\frac{f_a}{v}\left(\frac{dg}{dv}\right)dv \approx \left|\frac{dg}{dv}\right|_{v=v_{ao}}\int_0^\infty\frac{f_a}{v}dv \tag{14}$$

where

$$\frac{dg}{dv} = \sum_b n_b\left[\left(-\frac{1}{2}+Y_b{}^2\right)\frac{\Phi(Y_b)}{Y_b{}^2}+\frac{e^{-Y_b{}^2}}{\sqrt{\pi}Y_b}\right]$$

$\Phi(x)$ once again is the error function, and

$$\int_0^\infty\frac{f_a}{v}dv = N_a\left\langle\frac{1}{v_a{}^3}\right\rangle \tag{15}$$

As in the work by *Wentworth et al.* [1959], we approximate

$$\left\langle\frac{1}{v_a{}^3}\right\rangle \approx \frac{1}{\langle v_a{}^3\rangle} \tag{16}$$

And $v_a^3 = [(v_{ao}+\Delta v_{a//})^2 + (\Delta v_{a\perp})^2]^{3/2}$. If third- and higher-order terms in the expansion are neglected, we have

$$\begin{aligned}\langle v_a^3\rangle &\approx v_{ao}^3 + 3v_{ao}^2\langle\Delta v_{a//}\rangle + 3v_{ao}\langle(\Delta v_{a//})^2\rangle \\ &+ 1.5\,v_{ao}\langle(\Delta v_{a\perp})^2\rangle\end{aligned} \tag{17}$$

Spitzer [1962] evaluated the mean rate of change of the velocity and its squares over a short time t for a test charged particle moving in a plasma undergoing Coulomb interaction with the field particles. *Itikawa and Aono* [1966] expanded on the work of Spitzer; they included the energy lost by the test particle due to the radiation of plasma waves. This additional energy loss is not significant when the energy of ring current ions is below 1000 keV. Since only a small fraction of ring current ions have energies higher than 1000 keV [*Kistler et al.*, 1989], the "wave-component" of energy loss for ions can be ignored. However, for ring current electrons the velocity change due to the generation of waves becomes important at energies above 1 keV, which is near the peak of the ring current electron differential number density [*Huang et al.*, 1983]. In the following calculation, only the lifetimes of ring current ions are considered, so velocity changes due to wave generation are excluded. Velocity changes, derived by *Spitzer* [1962], are used. These are

$$\frac{<\Delta v_{a\parallel}>}{t} = -\sum_b \frac{A_D}{v_b^2}\left(1+\frac{m_a}{m_b}\right) G\left(\frac{v_{ao}}{v_b}\right) \tag{18}$$

$$\frac{<(\Delta v_{a\parallel})^2>}{t} = \sum_b \frac{A_D}{v_{ao}} G\left(\frac{v_{ao}}{v_b}\right) \tag{19}$$

$$\frac{<(\Delta v_{a\perp})^2>}{t} = \sum_b \frac{A_D}{v_{ao}}\left[\Phi\left(\frac{v_{ao}}{v_b}\right) - G\left(\frac{v_{ao}}{v_b}\right)\right] \tag{20}$$

where $A_D = 2n_b\Gamma_a$,

$$G(x) = \frac{\Phi(x) - x\Phi'(x)}{2x^2}$$

v_b is the thermal velocity of the field particles b.

After substituting (18) - (20) into (17), we have

$$\begin{aligned} <v_a^3> &= v_{ao}^3 - 3\sum_b A_D\left[\frac{v_{ao}^2}{v_b^2}\left(1+\frac{m_a}{m_b}\right) G\left(\frac{v_{ao}}{v_b}\right)\right] t \\ &+ \frac{3}{2}\sum_b A_D\left[G\left(\frac{v_{ao}}{v_b}\right) + \Phi\left(\frac{v_{ao}}{v_b}\right)\right] t \\ &= v_{ao}^3\left(1-\frac{t}{t_a}\right) \end{aligned} \tag{21}$$

where

$$\begin{aligned} t_a &= \frac{v_{a0}^3}{3\sum_b A_D\left[x^2\left(1+\frac{m_a}{m_b}\right) G(x) - \frac{G(x)}{2} - \frac{\Phi(x)}{2}\right]} \\ x &= \frac{v_{a0}}{v_b} \end{aligned} \tag{22}$$

Combining (14) to (16), (21), (22), and substituting into (13), we have

$$\frac{1}{\Gamma_a}\frac{\partial N_a}{\partial t} = \frac{\left|\frac{dg}{dv}\right|_{v=v_{ao}}}{2\, v_{ao}^3(1-t/t_a)}\frac{\partial}{\partial\mu}\left[(1-\mu^2)\frac{\partial N_a}{\partial\mu}\right] \tag{23}$$

We get an equation similar to the equation (22) in the paper of *Wentworth et al.* [1959]. However, there are two differences between these two equations: (1) The coefficient $\bar{n}$ is replaced by $0.5|dg/dv|_{v=v_{ao}}$. When v_{ao} is much larger than v_b, these two equations reduce to the same expression, because Wentworth assumed that f_b is a delta function. (2) The second difference is that τ_a is replaced by t_a and t_a does not reduce to τ_a even in the limit of $v_b \rightarrow 0$; there is a factor of 2 difference in the limit.

We write the Coulomb lifetime for ring current ions as

$$\tau = t_a\left[1-\exp\left(-\frac{2v_{ao}^3}{k' t_a \Gamma_a \left|\frac{dg}{dv}\right|_{v=v_{ao}}}\right)\right] \tag{24}$$

where τ is the time after which only $1/e$ of ring current species remain trapped. Since τ is a time constant of N_a, which is defined by (12) as the particle density per solid angle at pitch angle μ in velocity space, N_a can be reduced by being scattered into the loss cone and/or by a drop in the particle energy to zero (at $|v|=0$ in velocity space). Ring current ions are slowed down by the plasmaspheric electrons with no significant deflection. Therefore τ is the time after which only $1/e$ of ring current ions remain. The velocities of the rest of the population have been decreased to zero. These "zero-energy particles" are assumed to be removed from the trapping region.

In order to compare our result with that of *Wentworth et al.* [1959], another characteristic time, $\tau_{90\%}$, which is the time for 90% of the ring current particles to be lost from the trapping region, is calculated as a function of the ring current energy. We assume that in the plasmasphere

$$T_i = T_e = 1eV = T$$

For this comparison we use the same model for the plasmaspheric electron density as *Wentworth et al.* [1959] did and assume that electrons and protons are the only species in both the plasmasphere and ring current. Figure 1 shows the comparison of the calculated lifetimes in a Maxwellian-plasmasphere with those in a cold-plasmasphere (the latter can be derived from the former one by setting $v_b=0$). However, our

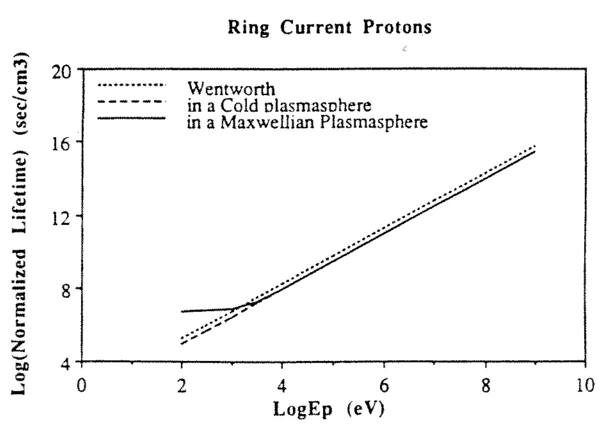

Fig. 1. The comparison of ring current Coulomb collision lifetimes in a zero-temperature plasmasphere and a Maxwellian plasmasphere. Plasmaspheric densities adopted in the *Wentworth et al.* [1959] study were also used in this calculation. The dashed line falls on top of the solid line when LogE_p is above 3.6.

expression for the lifetime in the cold (zero-temperature) plasmasphere is somewhat different from that obtained by *Wentworth et al.* [1959], because of the factor of 2 difference in $<v_a^3>$. It can be seen that the difference in proton lifetimes between a cold plasmasphere model and a Maxwellian one increases with decreasing energy, resulting in significant differences at low energies.

The Retarding Ion Mass Spectrometer (RIMS) carried by the DE 1 satellite made comprehensive measurements of the ion densities, temperatures, and flow velocities in the plasmasphere. The observations indicate that the major ions in the plasmasphere are H^+, He^+ and O^+. *Horwitz et al.* [1986] found, using RIMS data, that the relative abundances of the different ion species are quite constant in the plasmasphere from L equal 2 to 6. In our calculations of the Coulomb lifetimes of the ring current, we assumed that H^+, He^+ and O^+ are the only ions in the plasmasphere; their percentage abundances were taken to be *77%, 20%*, and *3%*, respectively. Other minor species were neglected. We also assumed a plasmaspheric ion density of 1000/cc, which is consistent with observations reported by *Horwitz et al.* [1986] for the outer plasmasphere. The value $ln\Lambda$ was taken to be 21.5.

Figure 2 shows the normalized lifetime $(n_e\tau)$ as a function of energy for each ion species in the ring current. Since we are looking for the bounce-averaged lifetime, we are only interested in particles with energies high enough so that their Coulomb lifetimes are much longer than their bounce periods.

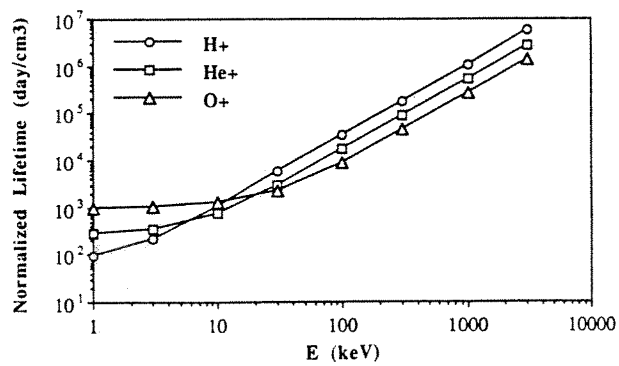

Fig. 2. Normalized lifetimes as a function of energy for each ring current ion species.

This condition is satisfied when the energy of the ring current ion is above 1 keV [cf. *Rycroft*, 1987]. The light species have longer lifetimes than the heavier ones at high energies, while the situation is reversed at low energies. The contribution of each plasmaspheric species to the ring current decay is depicted in Figure 3. It can be seen that only plasmaspheric electrons contribute significantly to the Coulomb decay of the ring current ions. Therefore the Coulomb loss of ring current ions is caused by energy transfer to the plasmaspheric electrons, and not by pitch angle diffusion, consistent with the prediction in section 2.

5. COULOMB DECAY VERSUS OTHER LOSS MECHANISMS

Coulomb collisions with plasmaspheric charged particles are not the only loss process for the ring current plasma. Other processes such as charge exchange and wave-particle interactions must also be considered. Different processes are dominant in different energy ranges or physical locations.

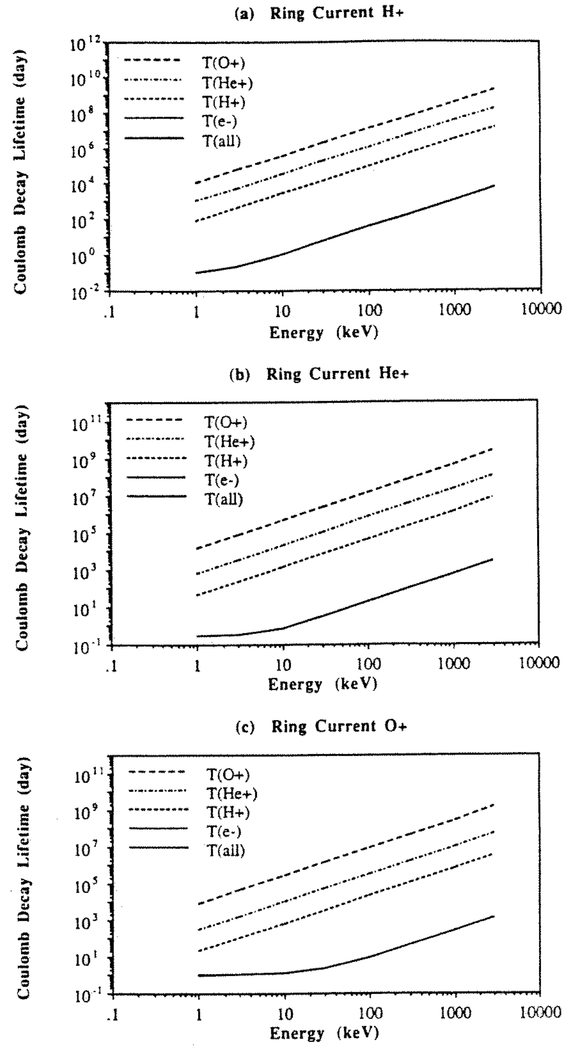

Fig. 3. The ring current Coulomb lifetime due to individual plasmaspheric species. Plasmaspheric densities of 1000/cc were assumed, 77% H^+, 20% He^+, 3% O^+. $T(O^+)$ is the lifetime if there is only O^+ in the plasmasphere and so on. $T(e\text{-})$ curves fall on top of T(all) curves.

Ring current ions can decay by charge exchange with neutral hydrogen atoms. The charge exchange lifetime is

$$\tau_{ex} = \frac{1}{n_H \sigma v} \tag{25}$$

where n_H is the number density of neutral hydrogen; σ is the charge exchange cross section; and v is the velocity of the ring current species.

Kistler et al. [1989] used the neutral hydrogen density values given by *Rairden et al.* [1986] and the cross-section values summarized by *Smith and Bewtra* [1978] to calculate the charge exchange lifetime of ring current ions. Their results are plotted in Figure 4, together with the Coulomb collision lifetime in thermal plasmas with densities of 2000, 1000, 500, 100, and 10/cm^3. *Kistler et al.* [1989] examined the ion energy spectra of four major magnetospheric ions during several equatorial storms (average Kp~6) in the time period from September 1984 to November 1985, using AMPTE/CCE data, and they found that, in the prenoon sector, the ring current loss rate at low energies was greater than could be explained by charge exchange only. It is shown in Figure 4, that at L=3.5, where

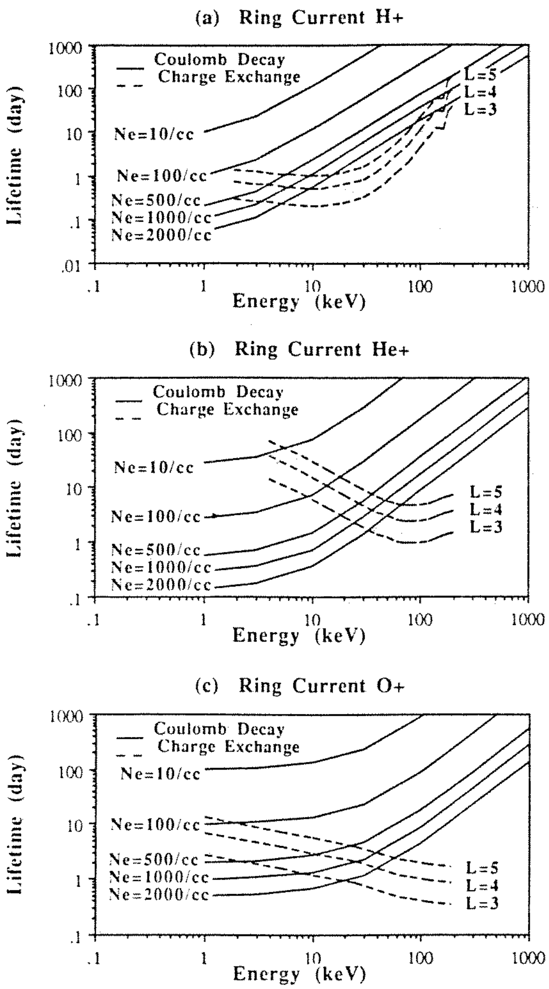

Fig. 4. The comparison of Coulomb decay lifetime and the charge exchange lifetime of ring current ions. Solid lines are Coulomb lifetimes and broken lines are charge exchange lifetimes. Coulomb decay lifetimes were calculated using Ne = 2000, 1000, 500, 100, and 10 cm^{-3}.

densities are typically ~1000/cm^3 under the same storm conditions (Kp=6, prenoon sector) [*Horwitz et al.*, 1990], Coulomb decay cannot be ignored when the energy of the proton is less than 7 keV or more than 200 keV and those of He^+ and O^+ are less than 30 keV. The above results indicate that Coulomb collision is a possible candidate to explain the discrepancy *Kistler et al.* [1989] have found.

Pitch angle diffusion caused by wave-particle interaction is another possible loss mechanism of the Earth's radiation belt. However, if strong pitch angle diffusion is taken into account, the modeled lifetime is always shorter than the measured one [*Kistler et al.*, 1989]. On the other hand, there is no explicit expression for the lifetime of ring current ions due to weak pitch angle diffusion, so it is hard to compare the importance of wave-particle interaction with other loss mechanisms for ring current decay. The role of wave particle interaction processes for the lifetime of ring particles is not understood at this time.

6. Discussion

Coulomb collision is one of the major interaction processes between the ring current and the plasmasphere. The results of *Wentworth et al.* [1959] have been used in the past to calculate Coulomb decay lifetimes [e.g., *Liemohn*, 1961]. As was shown in this paper, those calculated lifetimes are valid only for ring current protons with energies above 5 keV. During the last decade, observations have shown that there is an important He^+ and O^+ component of the ring current and also that there are significant populations in the lower energy range [*Gloeckler et al.*, 1987]. The modified formulation for Coulomb lifetimes, presented here, extends the validity of this approach to heavy ions and to lower energies.

Charge exchange is clearly the dominant loss process for ring current protons over most of the ring current energy range. When the ring current is dominated by protons, Coulomb collisions do not play an important role in the loss of the ring current population as a whole. However, when heavy ions are a significant component (i.e., during geomagnetic storm main phase and during solar maximum conditions), Coulomb collisions make a significant contribution to the loss of ring current particles. In addition, Coulomb interactions are important for a number of processes that couple the ring current to the ionosphere. An example of such a process is the energy transfer from ring current ions to the ionospheric plasma [*Kozyra et al.*, 1987].

The calculations of *Wentworth et al.* [1959] and the improved ones presented here did assume that the plasmaspheric densities encountered by the ring current particles are independent of their equatorial pitch angle. This is a reasonable assumption, because the bulk of the particles have large enough pitch angles to remain near the equator and thus the use of the equatorial density in the calculations does lead to reasonably accurate estimates for the lifetime of the bulk population. If one is interested in the evaluation of the actual velocity distribution of ring current particles, it is important to consider the pitch angle dependence of the densities that the particles encounter. No analytical solution to the problem can be obtained in that case; the equations have to be solved numerically.

7. Summary

We obtained an improved expression for the Coulomb decay lifetime of ring current ions, by assuming a Maxwellian distribution for the plasmaspheric plasma population. We found that Coulomb interactions are more important than charge exchange in determining decay lifetimes for ring current H^+, He^+, and O^+ below a few tens of keV. For realistic thermal plasma densities in the outer plasmasphere, Coulomb lifetimes for heavy ring current ions can be comparable to charge exchange lifetimes at energies near the peak of the ring current differential number density.

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